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FLEXIBLE COUPLING FOR A LIQUID COOLED COAXIAL TRANSMISSION LINE - PHASE I - FINAL REPORT

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SECTION 1

INTRODUCTION

Ship DC electric drives require large currents ranging from 100 to 200 kA at full power to develop the horsepower necessary to propel the ship. High current transmission lines are therefore required. These lines must be designed within external magnetic field specifications to reduce ship magnetic signature. Flexible couplings must be used with transmission lines to account for environmental factors such as line contractions and expansion, and to withstand the Navy environment which includes shock and vibration. Figure 1 shows how flexible couplers are integrated into the powertrain to minimize the vibration transmission between the motor and generator. Development of a flexible coupling is important to future application of high current transmission lines on ships.

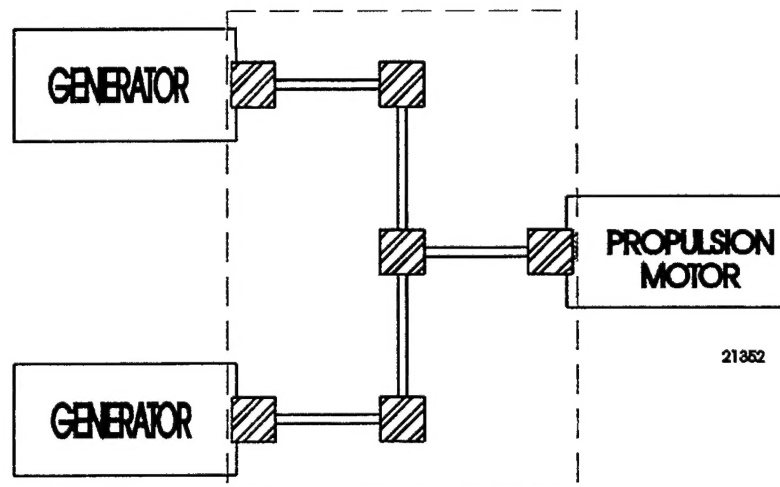


Figure 1. High current DC transmission.

Cooled flexible couplings for high power transmission lines that are cost effective, easy to fabricate, install, and maintain are required. The coupling should be designed with readily available components to minimize the cost of production. This reduces the cost impact of implementation, permitting rapid testing and integration.

In our Phase I effort, we collected the coupler design requirements. Upon our discovery that the transmission line geometry had not been chosen and the requirements list was incomplete, we conducted a bus configuration analysis of two candidate geometries, coaxial and interleaved plate systems, so that a flexible coupling concept design could begin. From our analysis, we determined that either configuration meets the requirements. We believe that the interleaved plate configuration is less costly to fabricate and can be used without forced cooling. Since some of design requirements and cost information are unknown at this time,

we were unable to recommend which transmission line configuration best fits the Navy's needs. The selection should be based on a system level trade.

With the design of the transmission line and the interface to the motor and the generator incomplete, a point design of a coupler is not appropriate. Instead we chose to develop a basic understanding of how flexible couplers work and the tools necessary to design and to analyze a given coupler. With a sound understanding of flexible couplers and the dynamics involved, the potential of candidate couplers to meet the requirements can be assessed. Once the design requirements are complete, a point design of a flexible coupler could be undertaken in Phase II.

We believe the flexibility can be provided with sliding members, such as brushes, or with flexural members. These members will be the interface between the generator and the transmission line. Concepts to interface with coaxial and interleaved plate lines, such as the one shown in Figure 2, are necessary. For this application, the flexible coupler may not require active cooling.

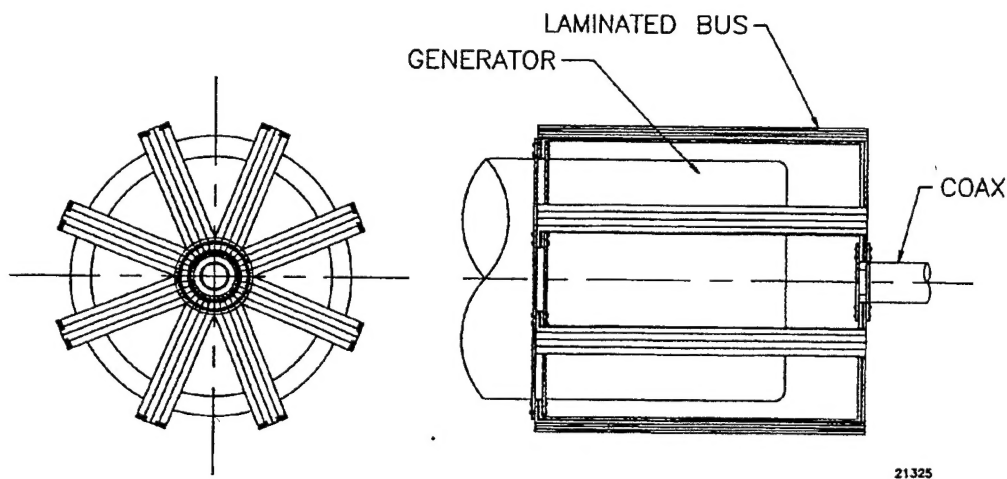


Figure 2. Our laminated flexible coupler concept.

This report is broken into six sections: Section 1 – Introduction; Section 2 – Design Requirements; Section 3 – Bus Configuration Analysis; Section 4 – Flexible Coupling Concept Design; Section 5 – Dynamic Analysis; Section 6 – Conclusions and Recommendations.

SECTION 2

DESIGN REQUIREMENTS

Early in this phase of the program, we conducted a kickoff meeting at Naval Surface Warfare Center (NSWC). The goal of this meeting was to outline the transmission line and flexible coupler design requirements. The meeting discussions concentrated on the state of technologies involved and on defining the list of requirements and specifications. A summary of the requirements and specifications, as agreed upon during the meeting, follow.

The requirements and specifications are broken down into mechanical, electrical, and environmental categories and are presented in Tables 1 through 3. No cost requirements were provided.

TABLE 1. MECHANICAL REQUIREMENTS

| Parameter | Requirement/Goal | Comments |
|--|--------------------|---|
| Weight, Size, Fixture & Conductor Length | | Conduct Tradeoff Analysis |
| Line Configuration | | Coaxial or Interleaved - Conduct Magnetic Emissions Analysis |
| Peak Thermal Expansion | + 3.6 in. | ΔT 115° 85° C MIL 17857 30° C RT Variation 60' Al |
| Coupling Configuration | Inline or "T" | |
| Motion Excursions - Vertical - Transverse, Axial | 3" 2" | |
| Misalignment - Angular - Vertical - Transverse, Axial | 5° 0.3" 0.2" | |
| Vibration Isolation | | Conduct Analysis of Stiffness Versus Frequency |

TABLE 2. ELECTRICAL REQUIREMENTS

| Parameter | Requirement/Goal | Comments |
|---------------------|------------------------------------|-------------------------------------|
| Current | 100 kA DC, Continuous | Conduct Tradeoff Analysis to 200 kA |
| Voltage Drop | Maintain 99.37% η | |
| Magnetic Signature | < 20 G Beyond 12" < 20 G/s Rate | MIL-STD-1399 |
| Operating Voltage | 200 V | |
| Fault Current | 10 X Higher ? | |
| Dielectric Strength | 1500 V for 1 Minute | |

TABLE 3. ENVIRONMENTAL REQUIREMENTS

| Parameter | Requirement/Goal | Comments |
|-------------------------------------|------------------|---------------|
| Maximum Exposed Surface Temperature | 85° C | MIL 17857 |
| Ambient Temperature | 0° C – 50° C | |
| Humidity | 0% – 95% | |
| Shock | Type A | MIL-S-901 |
| Vibration | Type 1 | MIL-STD-167-1 |
| Corrosion Resistance | | |
| Toxicity | | MIL-E-917E |

During the course of the meeting, we learned that the bus configuration had not been selected and the interface to the motor/generator has not been defined. The direction from NSWC was to ensure a transmission line efficiency of 99.37% based on a previous system efficiency study. (For 100 kA, the transmission line/coupler resistance budget can be determined from the line efficiency. Line cross section varies with equivalent line length as long as the line is within the allowable resistance.) Consequently, to begin our task, we analyzed the potential bus configurations before beginning flexible coupler design. The details of our analysis are contained in the following section.

SECTION 3

BUS CONFIGURATION

3.1 INTRODUCTION

To begin a flexible coupler concept design, the buswork configuration must be chosen. We examined two possible configurations, a coax and an interleaved plate configuration. Our evaluation was based on an overall comparison of the magnetic flux densities, thermal management, mechanical behavior, and cost.

Figure 3 shows IAP's concept of an 11 bar interleaved plate configuration which meets the requirements. It consists of five positive and four negative 42.1 mm by 421 mm buses, capped by two 21 mm by 421 mm negative buses. (The fifth negative bus is split, giving eleven, to minimize magnetic signature.) The bus plates are spaced 12.7 mm to allow for natural convection. For a 100 kA peak current, the current density is 1.1 MA/m² for a 15 m (50 ft.) length.

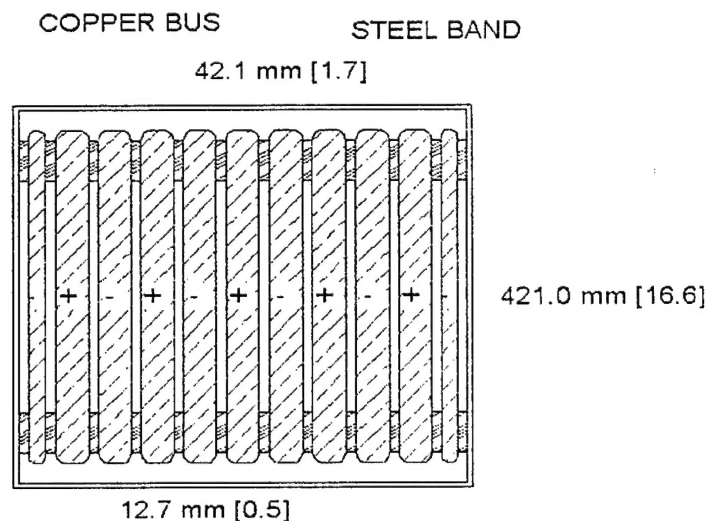


Figure 3. An eleven plate, interleaved configuration meets our requirements.

Given the requirements, interleaved plates are worthy of additional consideration by the Navy in choosing their buswork configuration. Magnetic signature considerations are not a discriminator. Both busbar configurations can be designed to meet naval requirements. Interleaved plates are more advantageous from a thermal management viewpoint, since it is difficult to cool the inner conductor of the coax. Mechanically, the coax has the advantage since the electromagnetic forces are taken in hoop not bending. With the cost information we have, we could not determine which busbar system was less expensive. Overall, without a system level trade study, we were unable to select between the two configurations.

In the following paragraphs, we present the details of our analysis.

3.2 Approach

We compared the coax configuration to an interleaved plate configuration based on the magnetic flux densities produced, on the temperatures reached by the conductors, on mechanical requirements, and on costs. We maintained an electrical efficiency of 99.37%, which was given in the information provided by NSWC at our kickoff meeting, which translates into a total line resistance budget of $6.75 \mu\Omega$. A 50 foot line length was chosen for all comparisons. The assumptions and details of each comparison are provided in the following sections.

3.3 Magnetic Signature

From the requirements generated in our kickoff meeting, the magnetic signature must be less than 0.002 T or 2 mT (20 G) at 0.3 m from the surface of the buswork per MIL-STD 1399. It is well known that the magnetic flux outside of a coaxial conductor is zero. To predict the magnetic flux emitted from an interleaved plate configuration, we referred to Zahn¹ for a closed-form solution in conjunction with an IAP inhouse finite difference magnetic computer code FMAGBAR. We also used our finite element computer code, MEGA, to map the magnetic field emitted from the bus.

Zahn gives the following equation for the magnetic field emitted from a single plate:

$$B = \frac{-\mu_0 K_0}{4\pi} \left[2 \tan^{-1} \left(\frac{wy}{y^2 + x^2 - w^2/4} \right) i_x + \ln \frac{(x+w/2)^2 + y^2}{(x-w/2)^2 + y^2} i_y \right] \quad (1)$$

where: B = the magnetic flux,
 μ_0 = the permeability constant,
 K_0 = the plate current per unit height (I/h),
 x and y = the distances from the plate centerline, and
 w = the plate height.

To determine the magnetic field emitted from a group of bus bars, the above equation can be used if the results for each plate are summed vectorially (superposition).

The above equation is applicable to plates with a height much greater than their width. Since the chosen

1. Zahn, Markus, Electromagnetic Field Theory, New York, John Wiley & Sons, Inc.

conductor geometry has an aspect ratio of approximately 10, we compared the results given from the above formula to that given by our inhouse finite difference computer code FMAGBAR. FMAGBAR predicts the magnetic field emitted from rectangular plates and bars of any aspect ratio. The comparison of the emitted magnetic field given by Zahn and our computer code for two busbars is presented in Figure 4. We concluded that Zahn could be used since the two methods gave identical results. This closed form method allows us to compare various configurations quickly.

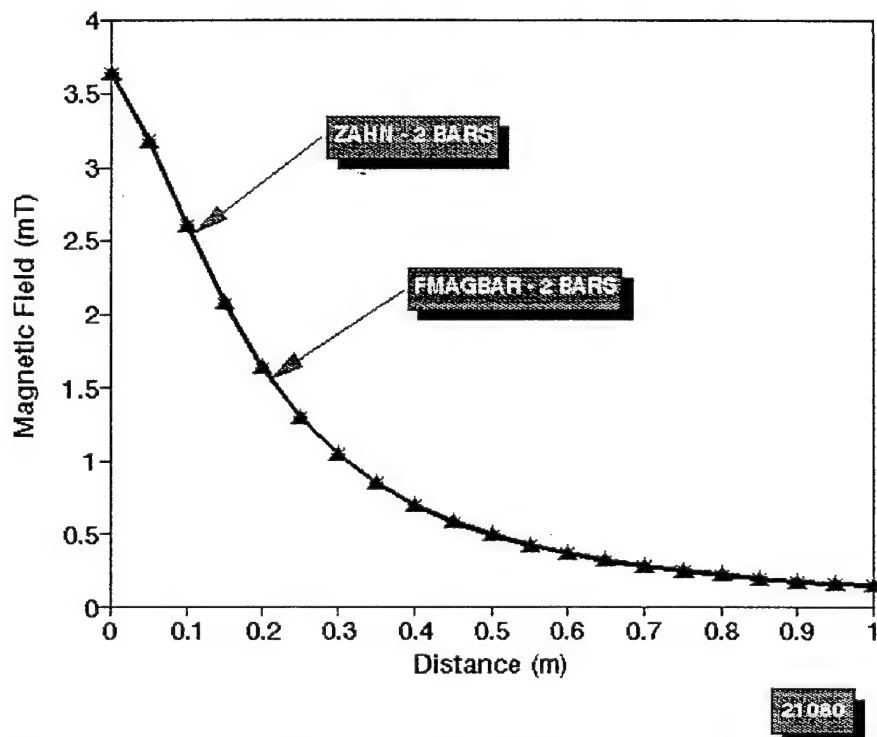


Figure 4. Our closed-form calculation and FMAGBAR results.

An eleven bar interleaved configuration consisting of five positive and four negative 42.1 mm by 421 mm buses, capped by two 21 mm by 421 mm negative buses meets the magnetic signature requirement. (The fifth negative bus is split, giving eleven, to minimize magnetic signature.) The magnetic flux density as a function of distance from the surface of the outer negative plate is presented in Figure 5. The magnetic flux is highest along a line extending from the outside corner of the plates. (At a distance of zero on the horizontal axis is the outer surface of the outer conductor.) However, the field quickly falls within the 12 inches (0.3 m) to less than 0.5 mT (5 G), well below the required 2.0 mT (20 G) limit.

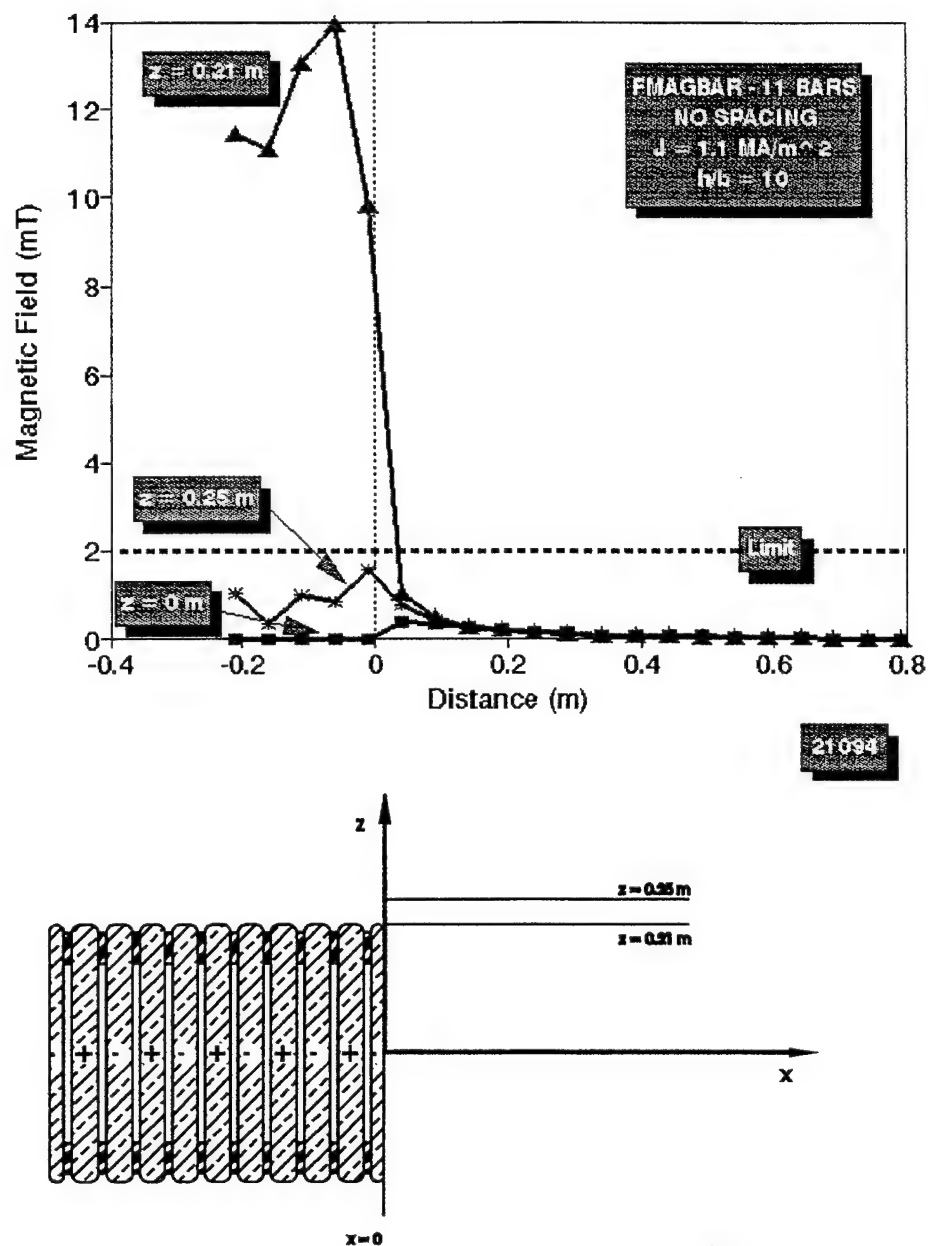


Figure 5. An eleven bar interleaved configuration meets the magnetic signature requirement.

3.4 Magnetic Finite Element Analysis

We conducted magnetic finite element analysis (MEGA) of the interleaved busbar configuration so that we could easily map the bus magnetic signature. Using a quarter symmetry, DC model, we confirmed that the magnetic fields from the interleaved buses are within the limit. As shown in Figure 6, a color contour plot of the magnetic flux emitted from the bus, the fields are highest at the corners of the interleaved plates. Figure 7 is the magnetic flux density plotted along the centerline from the surface of the outer negative plate. The magnetic field strength is approximately 0.5 mT or 5 G at 150 mm (6 in.), well within the requirements. Along the centerline of the other axis, the field is less than 0.1 mT or 1 G at 150 mm. The magnetic field extending from the corner of the interleaved plates is presented in Figure 8. At 1 mT (10 G) at a distance of 150 mm, the flux density is also within the requirements. Generally, the MEGA results agree well with our closed form results.

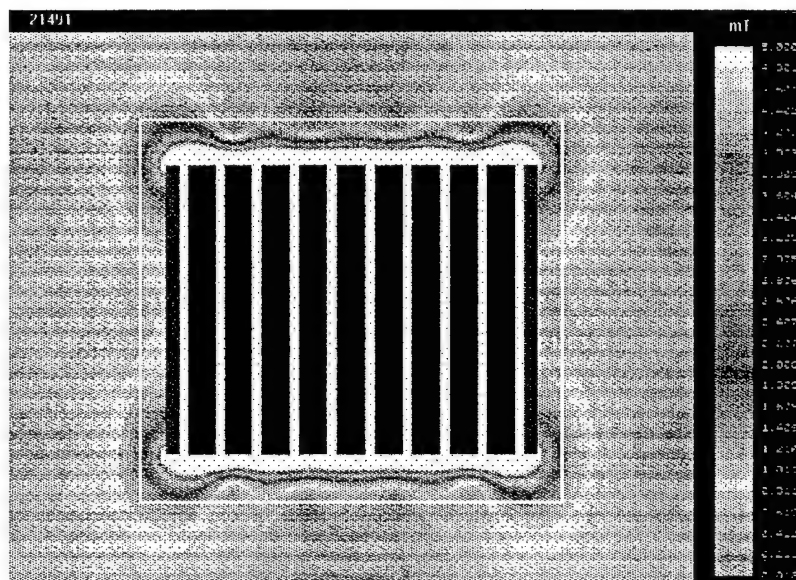


Figure 6. From the contour plots of the magnetic signature of the interleaved plate design, we determined the interleaved plate concept can meet the requirements.

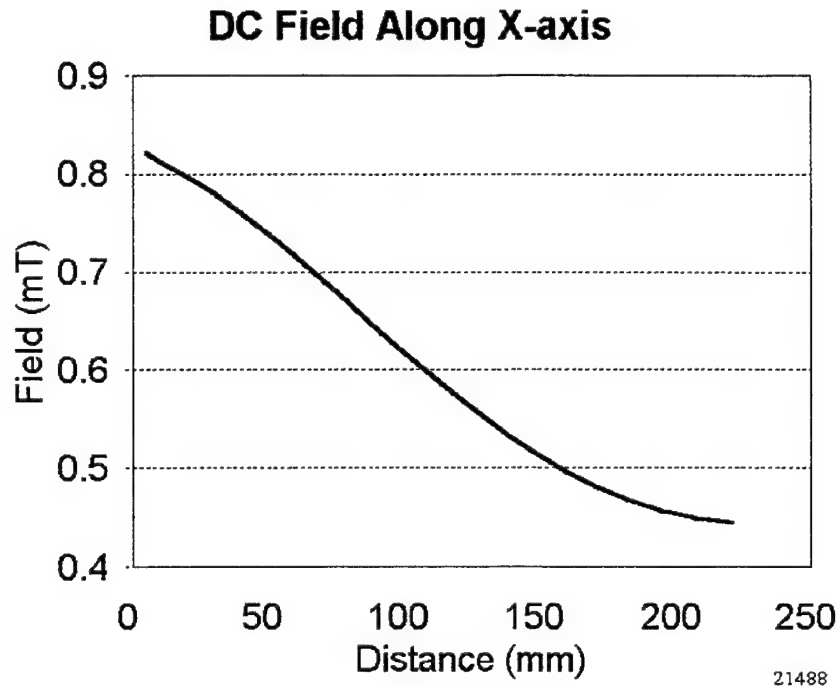


Figure 7. The field is 0.5 mT at 150 mm (6 in.) from the center of the outer surface.

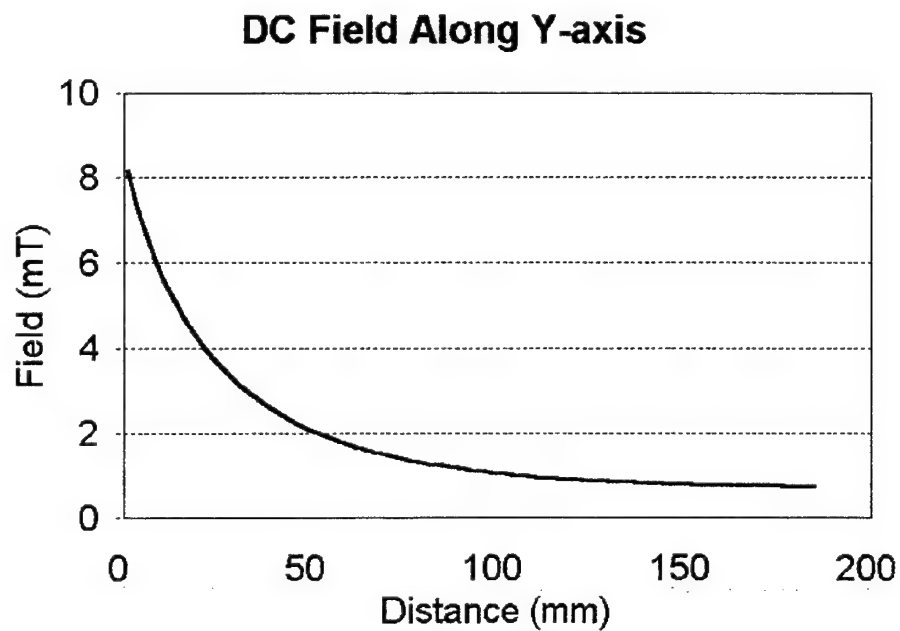


Figure 8. MEGA predicts the magnetic flux density of approximately 10 G at 150 mm extending from the corner of the interleaved plates.

3.5 Thermal Management

Figure 9 shows the temperature rise of the outer coaxial conductor and outer plate surface in the interleaved concept with varying heat transfer coefficient on the outer conductor surface. A 0.5 mm electrical insulation with a conduction coefficient of 0.25 W/mK was used in the comparison. Convection between the plates is assumed for the interleaved plate configuration. For the coax, the outer surface is used. High temperatures will occur in the coaxial configuration at low heat transfer coefficients, those typical of free convection. From Figure 10, with a smaller upper limit of the vertical axis, high heat transfer coefficients are necessary with the coax to meet the thermal requirement of a maximum temperature rise of 85° K. Therefore, forced convection cooling is necessary. The interleaved plates require low convection coefficients of 5 W/m²K to meet the requirement and can be cooled with natural convection.

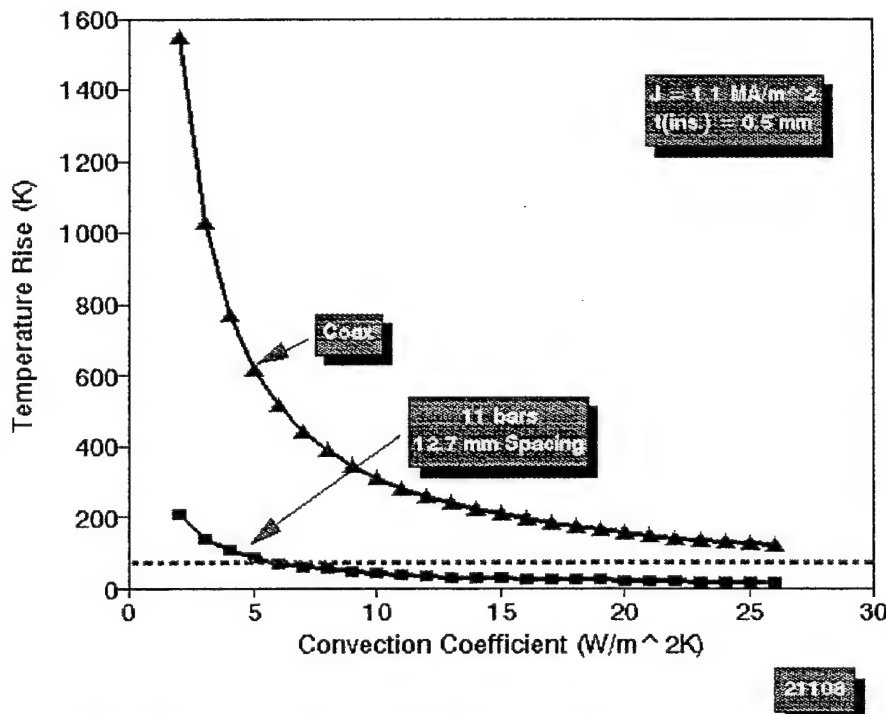


Figure 9. Outer temperature comparison between the coaxial line and interleaved plate.

Limited surface area of the coax results in high required heat transfer coefficients. For a maximum temperature rise of 85° K, forced liquid convection will be necessary with a coax configuration. In contrast, the interleaved plates provide substantially more surface area and can be spaced to allow natural convection.

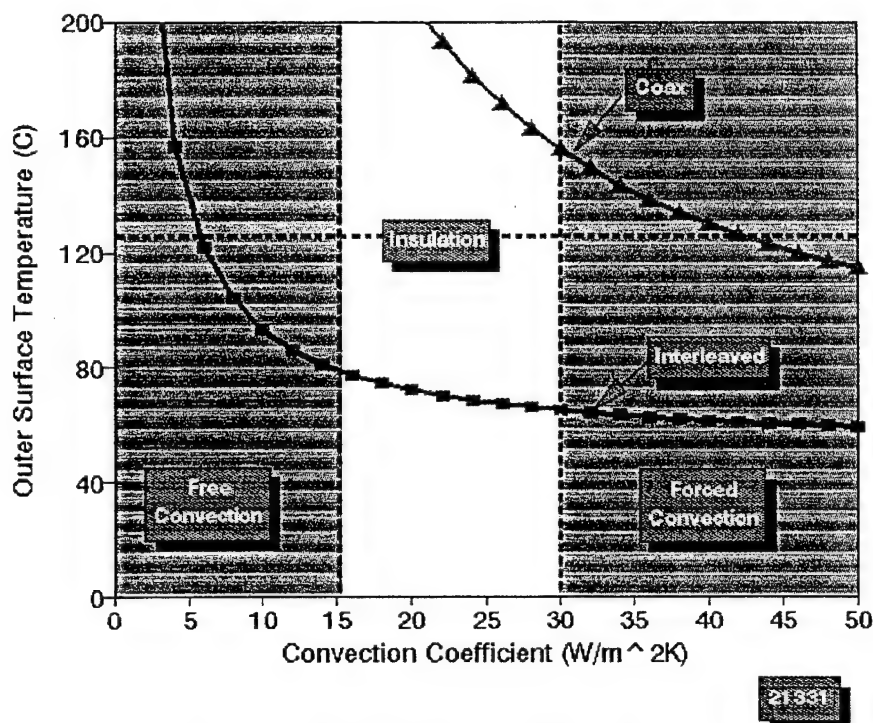


Figure 10. Convection coefficients of 40 W/m²K and 5 W/m²K are required for the coax and the interleaved plate configurations, respectively.

3.6 Mechanical Behavior

Assuming equal distribution of current throughout the coaxial conductors, a coax configuration does not produce unbalanced forces on either conductor. However, there are internal pressures generated due to the high fields confined in the coax, as illustrated in Figure 11. Assuming there are no internal coolant channels within the inner coaxial conductor, the stress is highest for the outer conductor. This conductor can be modelled as cylinder with an internal pressure. The pressure is highest in the fault condition, which we assumed to be ten times the rated current of 100 kA. The pressure is given by:

$$P = \frac{IB_{ave}}{2\pi r_i} \quad (2)$$

where:

- P = the internal pressure,
- B_{ave} = the average magnetic field within the outer conductor, and
- r_i = the inner radius.

The average magnetic field is given by:

$$B_{ave} = \frac{\mu_o I}{2\pi(r_o - r_i)} \ln \frac{r_o}{r_i} \quad (3)$$

where: r_o = the outer radius of the outer conductor.

For a fifty foot length, the inner radius is 0.178 m (6.97 in) and outer radius is 0.238 m (9.37 in). The average magnetic field within the outer conductor is 0.97 T. The corresponding pressure is 0.9 MPa (125 psi).

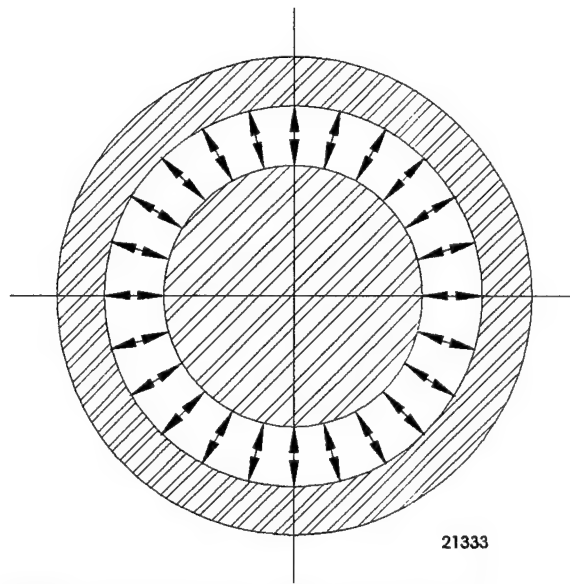


Figure 11. With coaxial busbars, an internal pressure is generated.

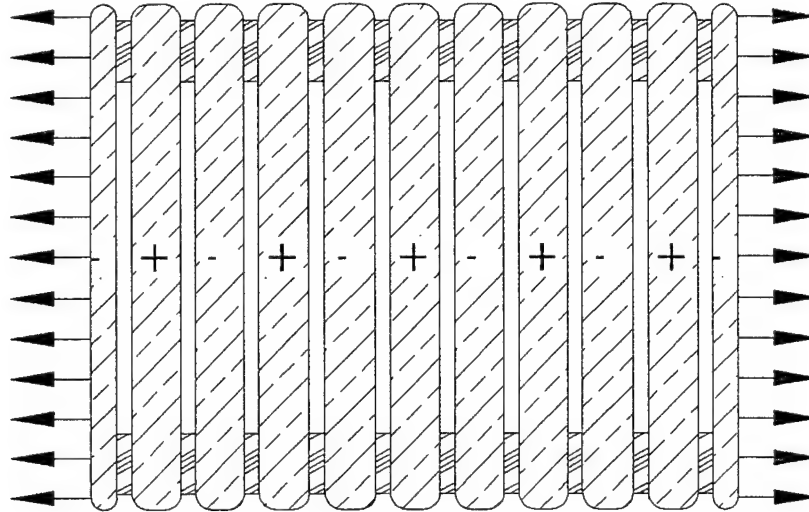
The tangential stress, σ_t , in the conductor is given by:

$$\sigma_t = P \frac{(r_o^2 + r_i^2)}{(r_o^2 - r_i^2)} \quad (4)$$

For the fifty foot length, this gives a tangential stress of 3 MPa (0.4 ksi). This stress is well within the capabilities of copper.

For an interleaved configuration of parallel plates, the configuration is not balanced. Assuming equal current distribution through the plates and equal current sharing among the plates, there is an outward net force

on the outer plate as illustrated in Figure 12. This force is highest in a fault condition (which we assumed to be ten times the rated current of 100 kA).



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Figure 12. With interleaved plates, an outward net force exists on the outer plate.

The force must be counteracted so that large deflections and stresses do not occur in the outer bus plate. This can be accomplished with steel straps. To determine the required spacing of the straps, the outer plate can be modelled as a beam with fixed supports and a uniformly distributed applied load. The net loading on the outer plate was calculated from our magnetic finite element analysis (MEGA) and is equal to 13.4 kN/m for the fault current. The yield stress for half hard copper is 220 MPa (32 ksi). The accompanying stress is given by:

$$\sigma = k_s \frac{Mc}{I} \quad (5)$$

where: σ = the stress,
 k_s = the safety factor,
 M = the moment,
 c = the distance from the neutral axis, and
 I = the area moment of inertia.

In this case, the moment is given by:

$$M = \frac{\omega l^2}{12} \quad (6)$$

where: ω = the distributed load, and
 l = the unsupported beam length.

Calculating the required length (using a safety factor of 2) gives a distance between supports of 1.75 m.

The accompanying deflection is given by:

$$\delta = -\frac{\omega l^4}{384 EI} \quad (7)$$

where: δ is the deflection, and

E is the material's modulus of elasticity, 120 GPa for copper.

This results in a deflection of 8.0 mm, which is large for a 12.7 mm spacing between plates. A more conservative approach would be to use a strap spacing of 1.25 m, reducing the deflection to 2 mm.

To determine the total bearing pressure on the strap, the reaction forces at the supports for each busbar must be calculated and summed. The reaction force for an individual busbar, R , is given by:

$$R = \frac{\omega l}{2} \quad (8)$$

The busbar forces are presented in Figure 13. Summing gives a total of 8.8 kN (2,000 lbs). The resulting bearing stress on the support, assuming an area of 0.0025 m² (4 in²) is approximately 6.8 MPa (1.0 ksi). This is well within the allowable limits for a plastic insulating material.

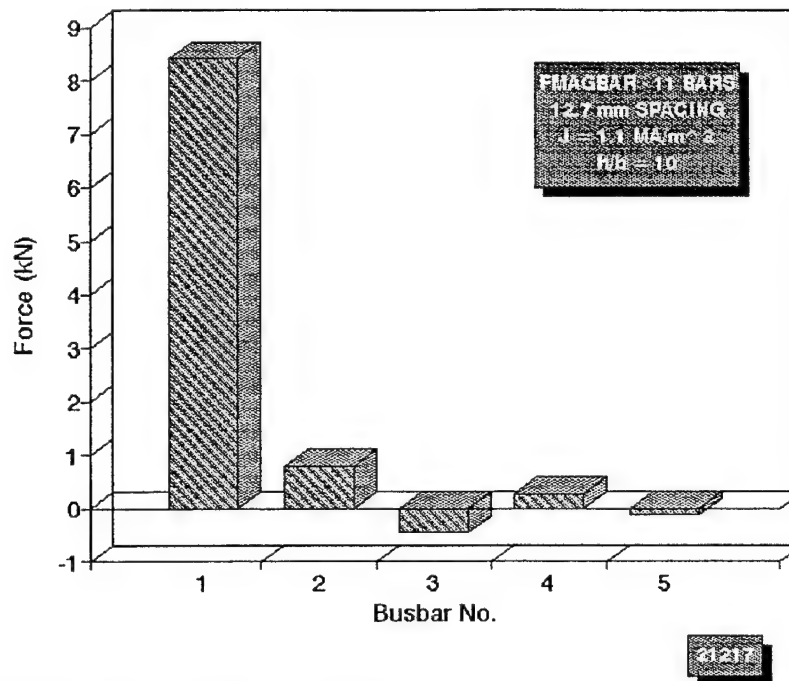


Figure 13. Interleaved busbar force distribution.

A steel band encircles our busbar concept at 1.25 m intervals to counteract these forces. With a 6.35 mm by 50.8 mm (0.25 in by 2 in) band, the tensile stress is 23 MPa (4 ksi). This stress is well within the allowable stress for steel.

The steel bands could also be used to support the weight of the buswork. Similarly, the plates could be modelled as beams with distributed loads on simple supports. At a spacing of 1.25 m, the additional stress due to the weight is low, 27 MPa (4 ksi).

Overall, the components required for the interleaved configuration result in low mechanical stress. Since the supports and steel band could be integrated with other hardware which may be necessary to support the buswork, these parts will not substantially effect the cost or the complexity of the bus assembly. As a result, we conclude that mechanical issues can be resolved with either configuration.

3.7 Cost Considerations

Although little cost information is available, a comparison of a coax and interleaved configuration would not be complete without considering the costs involved. The cost information available to us is presented in Table 4.

TABLE 4. LITTLE IS KNOWN ABOUT THE COST OF EITHER COAXIAL OR INTERLEAVED PLATE SYSTEMS.

| | Coax | Interleaved |
|--------------|---------|-------------|
| Material | \$3/lb. | \$3/lb. |
| Forming | 0 | 0 |
| Assembly | ? | ? |
| Installation | ? | Same |
| Maintenance | ? | ? |
| Repair | ? | ? |

Material costs would be the same regardless of the chosen bus configuration. The electrical efficiency requirement dictates or sets the amount of required material.

The forming costs would be small in comparison to the material costs due to the large amount of material required. It could be extruded for the cost of the material.

It will be difficult and expensive to assemble the coax compared to the interleaved plates. One method of assembling coax of long lengths is to make the outer conductor of multiple parts, maybe halves, and seam weld them together. However, this technique would make maintaining a plastic electrical insulator impossible. This would force the use of ceramic insulation, which would further drive up costs. The interleaved plate system would be much simpler and less expensive to assemble.

Installation costs would be similar for either busbar configuration. The same is true of maintenance and repair.

3.8 Summary and Conclusions

The interleaved plate concept is worthy of the Navy's additional consideration in choosing their buswork configuration. A summary of the results of our busbar system analysis is contained in Table 5. Magnetic signature considerations are not a discriminator. Both busbar configurations can be designed to meet naval requirements. Interleaved plates are more advantageous from a thermal management viewpoint, since it is difficult to cool the inner conductor of the coax. Mechanically, the coax has the advantage since the electromagnetic forces are taken in hoop not bending. With the cost information we have, we could not determine which busbar system was less expensive. Unable to select between the two configurations without

a system level trade study, we carried both coaxial and interleaved configurations into our flexible coupling concept design.

TABLE 5. BUSBAR ANALYSIS SUMMARY

| | |
|--------------|--------------------------|
| Magnetics | Not a Discriminator |
| Thermal/Size | Favors Parallel Plates |
| Mechanical | Favors Coax |
| Cost | Need More Information |
| Selection | System Level Trade Study |

SECTION 4

FLEXIBLE COUPLER CONCEPT DESIGN

4.1 Introduction

Flexible couplers must be designed to account for environmental factors, such as transmission line contractions and expansions, and to withstand the Navy environment which includes shock and vibration. The flexible coupler must also reduce vibration transmission between the motor, generator, and line. If the coupler can provide adequate vibration isolation, then it can be designed to withstand line contractions and expansions.

At this time, the design requirements are incomplete. As a result, we cannot select the most efficient flexible coupler for this application and proceed with a point design of the coupler. Instead we chose to develop a basic understanding of how flexible couplers work and the tools necessary to analyze a given coupler. With a sound understanding of flexible couplers, the potential of candidate couplers to meet the requirements can be assessed. Once the design requirements are complete, a point design of a flexible coupler could be undertaken.

Basically, flexible couplers provide vibration isolation in two ways, by promoting sliding between conductors through a low shear interface while maintaining electrical contact or by promoting flexure of a "weak" member. Examples of the use of sliding to provide isolation are earthquake resistant building foundations and electrical brushes. Sliding is the method behind multilam, which is shown in Figure 14. Bellows type connectors, braided connectors, and cables are examples of flexible couplers which utilize flexure to provide isolation. Both means can be designed to provide isolation in at least three degrees of freedom required in this application.

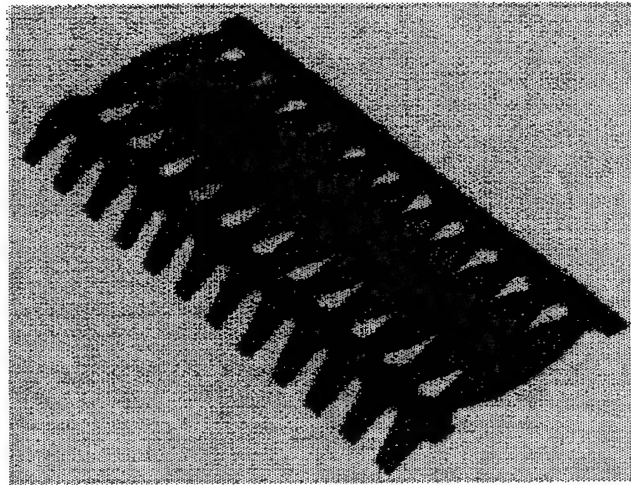


Figure 14. Multilam uses unidirectional sliding to provide isolation.

In the following paragraphs, the design tools for each coupler type are presented starting with those that promote sliding.

4.2 Sliding Flexible Couplers

Flexible couplers that promote sliding as a means of vibration isolation utilize a low shear interface while conducting electrical current. An example is electrical brushes. The interface can be dry or lubricated. In the extreme, the interface is liquid. Liquid flexible couplers are used in other applications. In this application, it is possible to use liquid metal to conduct current in such a design. In dry or lubricated sliding, the coupler must maintain the required contact force to conduct current without arcing.

IAP has extensive experience in the design of sliding contacts through our expertise in railgun armature contact design and testing, as well as numerous programs involving the design and testing of current collectors for homopolar generators/motors. We have built and tested current collectors with contact densities of 10^6 contacts/m² while maintaining contact pressures of 1 MPa. We have operated these collectors at current densities as high as 30 MA/m² and have demonstrated resistance densities of 1 to 10 n Ω -m². Although the sliding velocities of a flexible coupling are not as high as those in these applications, the basic design concepts are the same.

A sliding electrical contact design is driven primarily by the maximum current, number of contact points (spots), and the contact joint pressure applied. The total power losses of the contact joint can be calculated using the following basic relationship:

$$W_t = \mu P v + j^2 (\rho_c + \rho_b) \left(\frac{H}{n \pi P} \right)^{1/2} + \sigma_f \frac{H}{P} \quad (9)$$

| | | | |
|-------|------------|---|---|
| where | W_t | = | total contact power loss |
| | P | = | macroscopic contact pressure |
| | μ | = | coefficient of friction |
| | v | = | sliding velocity |
| | j | = | contact current density |
| | ρ_c | = | contact material resistivity |
| | ρ_b | = | bus material resistivity |
| | H | = | hardness of the softer of two materials |
| | n | = | number of contact spots per unit area |
| | σ_f | = | coefficient of film resistance |

From these losses and the data for a specific contact design, the resulting maximum contact spot temperature was determined using an in-house computer program developed by IAP. By choosing a particular material combination, the maximum, allowable spot temperature for the materials chosen to ensure long collector or brush life, and a peak current density, the relationship between contact spot density and contact pressure can be determined.

For silver plated copper on copper contacts with a maximum spot temperature of 550°K (material softening temperature), this relationship is shown in Figure 15 for several current densities. Specific design points for a typical Multilam contact and one of IAP's homopolar current collector designs are shown in the figure. Also included in the figure is our flexible coupling bus concept design current density of 1 MA/m².

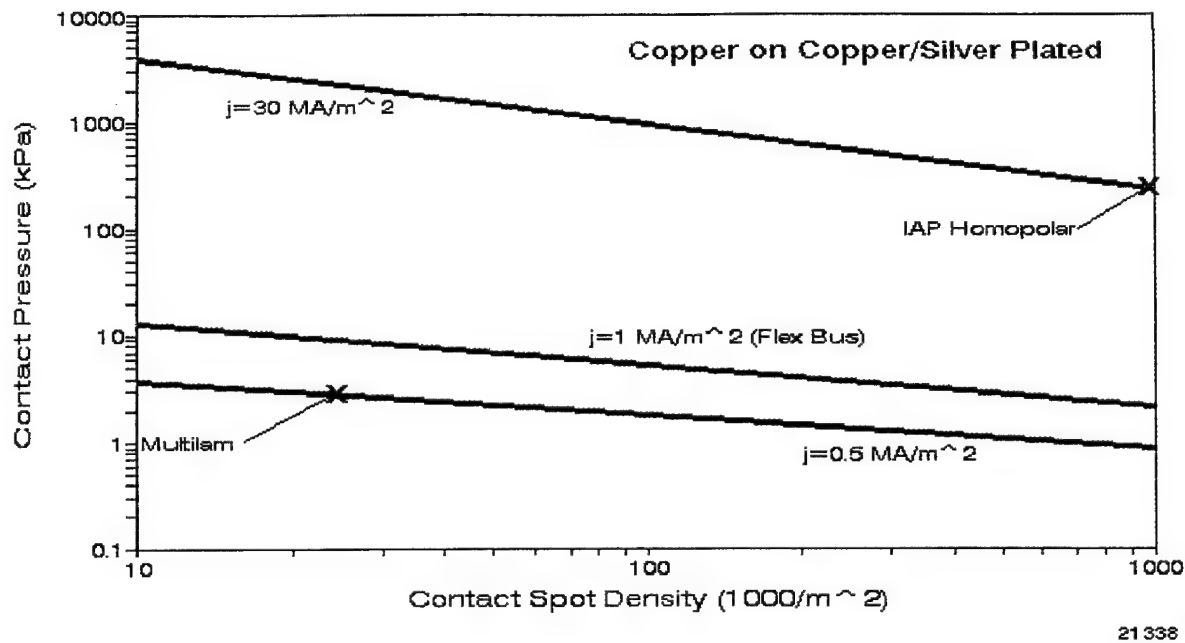


Figure 15. Required contact force varies with contact spot density.

To minimize the sliding force of a particular design, it is desirable to maximize the contact spot density. Two examples of contact subdivision are shown in Figure 16. One is multilam. These contacts are fairly simple to fabricate and to install and have relatively low contact spot densities. They are typically rated for current densities below 1 MA/m². The other example is IAP's finger type metal contact, depicted in a typical homopolar current collector design. They are more difficult to fabricate but have higher spot densities. They operate at much higher current densities (30 MA/m²).

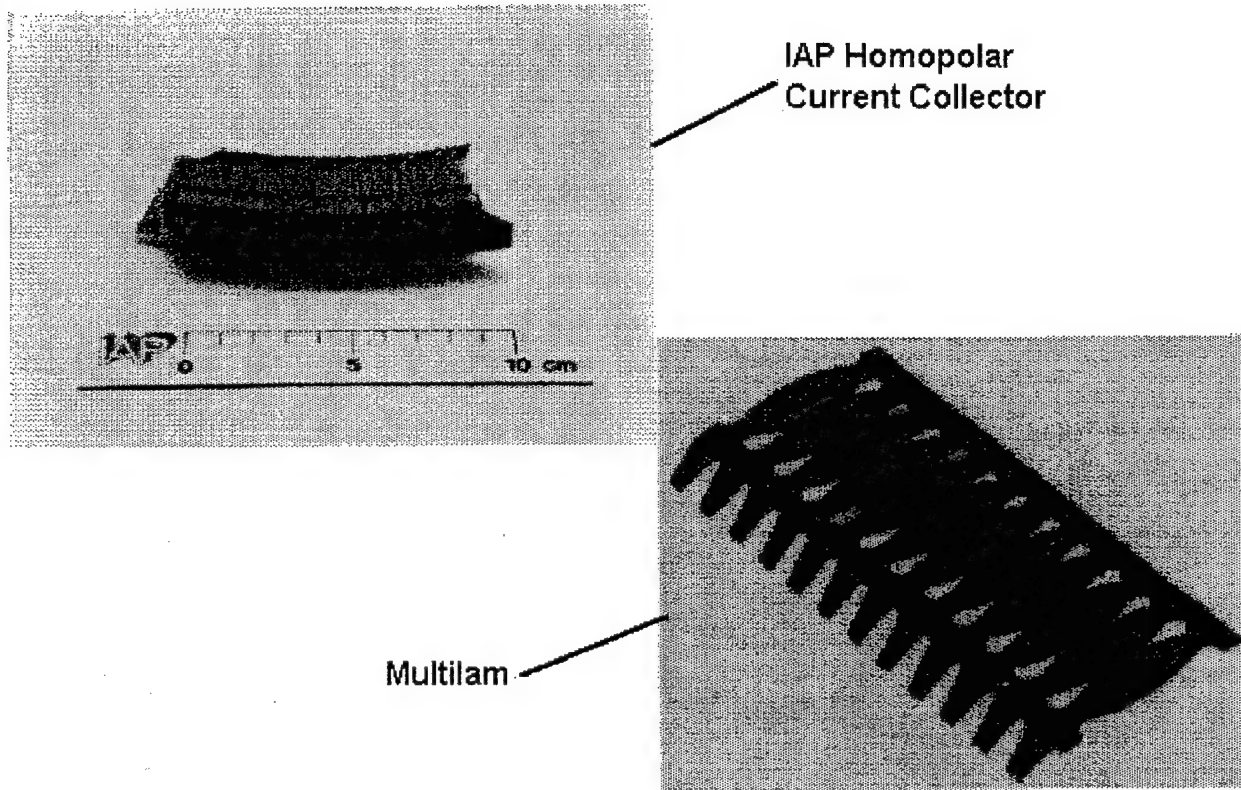


Figure 16. Contact subdivision can be achieved in many ways.

Generally, one must tradeoff between increasing contact subdivision which decreases overall joint size at the cost of increased sliding force. For a particular current level and desired sliding force, this results in the "safe" operating zone shown in Figure 17. Figure 17 incorporates the important design relationships and is useful in selecting a design or in conducting concept trade studies.

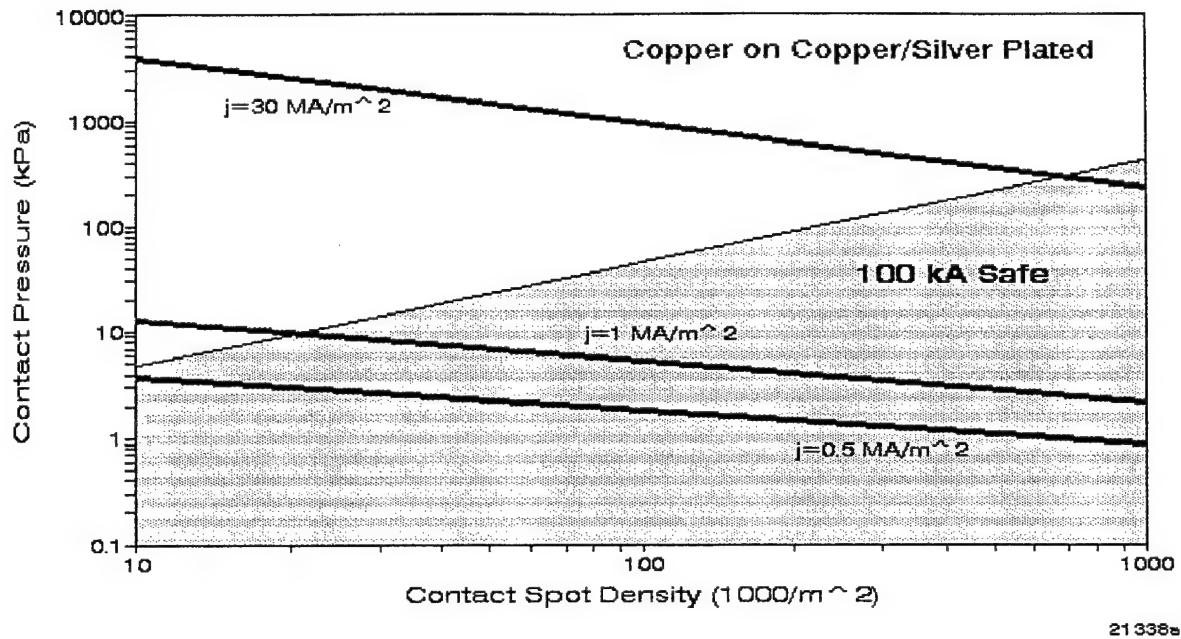


Figure 17. A "safe" operating zone exists for a 100 kA design.

In addition to the actual sizing of the contact area, there are other design issues and constraints which must be considered. How the contact pressure is applied, how the dissipated heat is removed, how the manufacturing tolerances are compensated, and how to provide an adequate range of motion must be resolved.

In general, sliding contacts have two orthogonal degrees of freedom which lie in the plane of the contact surface. In order to provide three orthogonal translational degrees of freedom, two independent sliding contact areas would be necessary, as shown in Figure 18. The overall size of the joint will also be influenced by the need to maintain the contact surface area during motion in a particular direction, as shown in Figure 19.

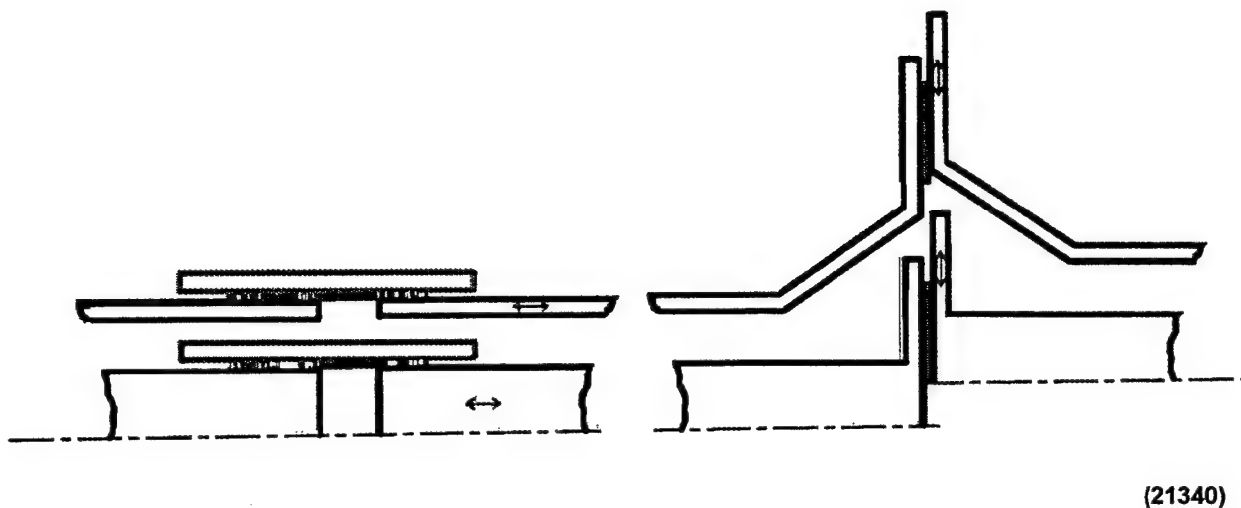


Figure 18. For two orthogonal degrees of freedom, two independent sliding contact areas are required for a coax.

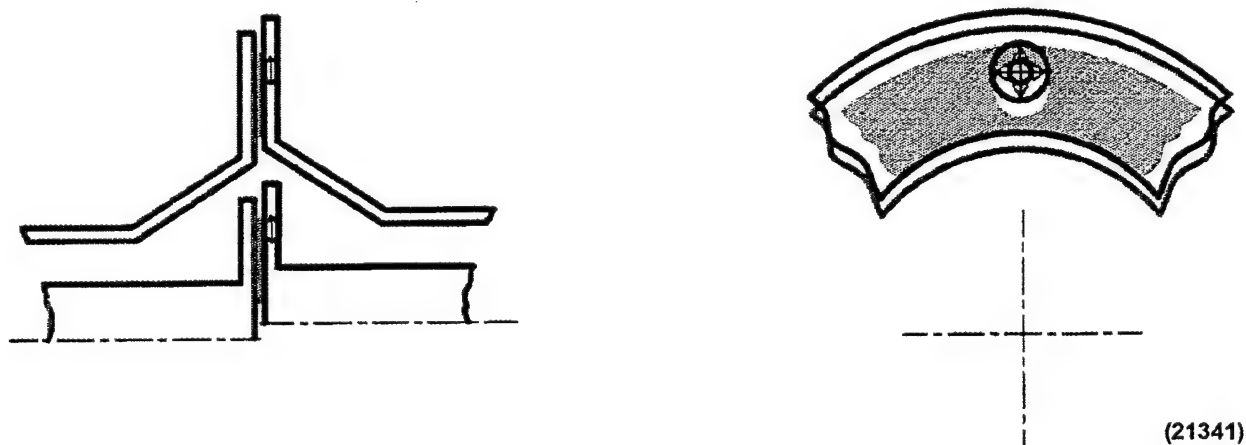


Figure 19. A larger sliding area is required to ensure electrical contact is maintained over the mating surface during lateral motion.

4.3 Flexure Members

Flexure, illustrated in Figure 20, is a commonly used vibration isolation mechanism. Vibration isolation of bellows type connectors, braided connectors, and cables come from this mechanism. Each of these examples has a pitch. (The stiffness of a cable, for instance, would be higher if the cords were not wound.) For a basic understanding of flexure, we modelled one quarter of a period as a cantilever. The deflection of the free end can be calculated from the following equation:

$$\frac{d^2y}{dx^2} = \frac{M(x,y)}{EI} \quad (10)$$

where y = the deflection,
 x = the distance along the cantilever,
 M = the applied moment,
 E = the material's modulus of elasticity, and
 I = the section modulus.

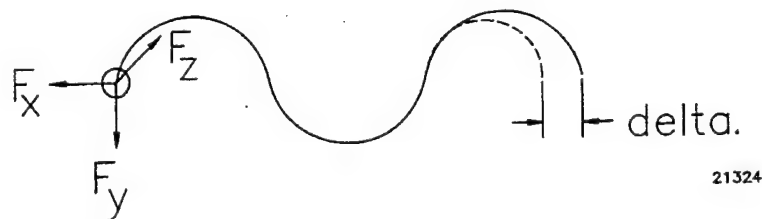


Figure 20. Flexure of a "weak" member can provide isolation.

The derivation of the above equation contains the assumption that the deflection is elastic. It is difficult to envision an acceptable coupler design which allows plastic deformation. The coupler should be designed within the material's elastic limit.

Often, in typical beam theory, the deflections are small in comparison to the beam length and the moment, M , does not change with the deflection. The moment is assumed to be only a function of the distance along the cantilever. In the case of a flexible coupler, large deflections may occur. To determine its effect, we numerically integrated the above equation allowing the moment arm to change with deflection. We also calculated the deflection assuming the moment does not change with deflection from:

$$\delta = \frac{Fl^3}{3EI} \quad (11)$$

where δ = the deflection of the free end,
 F = the applied force, and
 l = the length (accounting for the included angle).

We determined that the deflection calculated from the above equation is approximately 10% greater than the deflection calculated accounting for the change in moment with deflection. At this phase of coupler development, we assumed that the accuracy provided by the above equation is acceptable.

A more useable form of the deflection equation is to determine the transmitted force, F , in terms of the current capacity of the coupler. The current, I , can be calculated from the required current density, j , and the cross sectional area, A . In equation form:

$$j = \frac{I}{A} \quad (12)$$

To combine equations, the section modulus must be known in terms of area. For a rectangular geometry, the relationship is:

$$I = \frac{Ah^2}{12} \quad (13)$$

where h = the beam height.

By combining equations and separating into non-dimensional groups, the transmitted force per unit of current is given by:

$$\frac{F}{I} = \frac{E}{4j} \left(\frac{\delta}{l} \right) \left(\frac{h}{l} \right)^2 \quad (14)$$

With the above equation, one can see how the flexible coupling can be sized to give any given amount of isolation. By allowing the current density to increase, the transmitted force decreases since less cross sectional area is required. As the required deflection increases, the transmitted force increases linearly. (This results from our assuming only elastic deformation occurs.)

As the height decreases, the transmitted force decreases substantially. This is the idea behind laminated buswork, an example of which is shown in Figure 21. The highly flexible buswork was designed for a recent current collector program², which operated at a current of 100 kA. For multiple degree of freedom isolation, the conductor could be laminated in multiple planes.

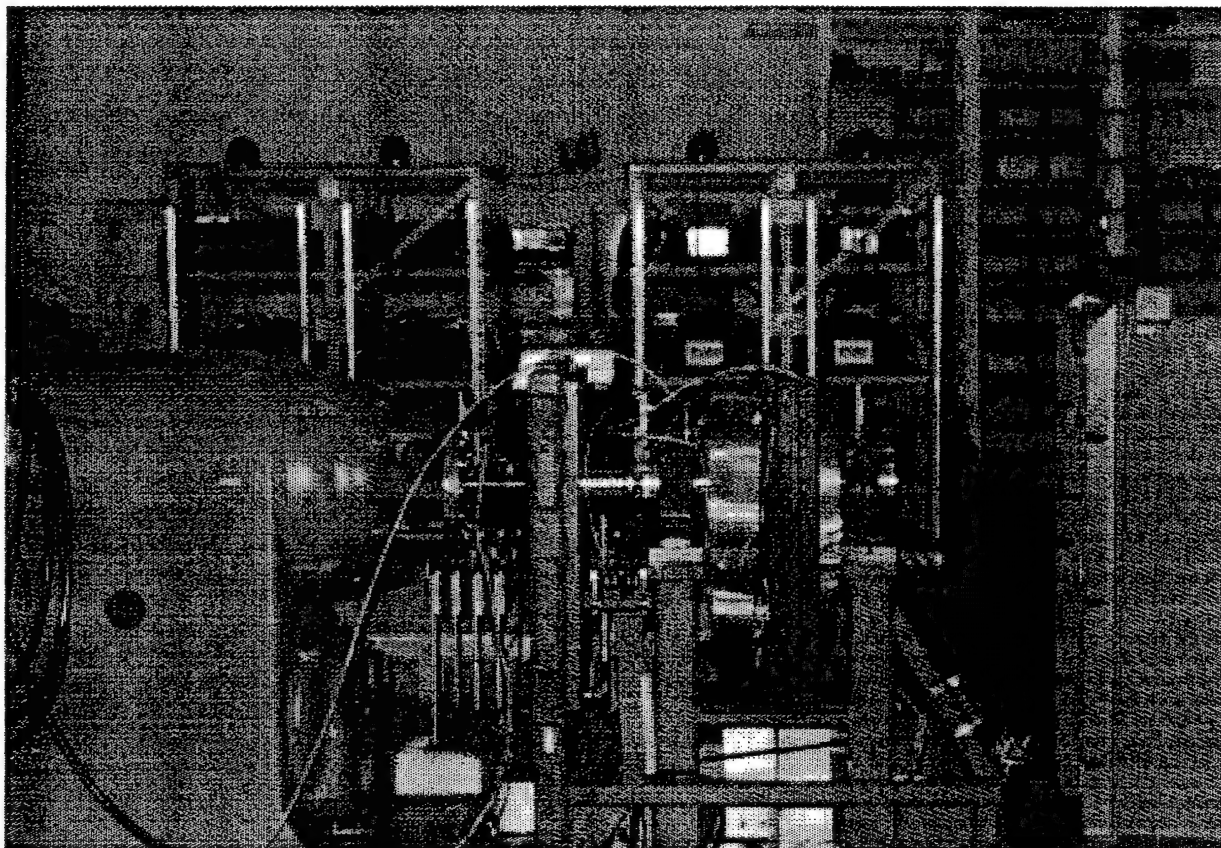


Figure 21. 100 kA flexible bus.

Figures 22 and 23 illustrate how a flexible system would be arranged for a coaxial and an interleaved plate transmission line, respectively. A generator with a ring interface geometry of approximately 3 m is shown. In both cases, laminated buses run from the generator tabs to the transmission line. With the laminated buses and large size, both interfaces allow the necessary isolation without any additional devices. Both polarities would be bused together lessening the magnetic signature and inductance of the coupler.

2. Antonios Challita, Brenton K. Ahrens, and David P. Bauer, "Current Collector Technology For Continuous Duty HPG," WRDC-TR-90-2102, Final Report, November 1990.

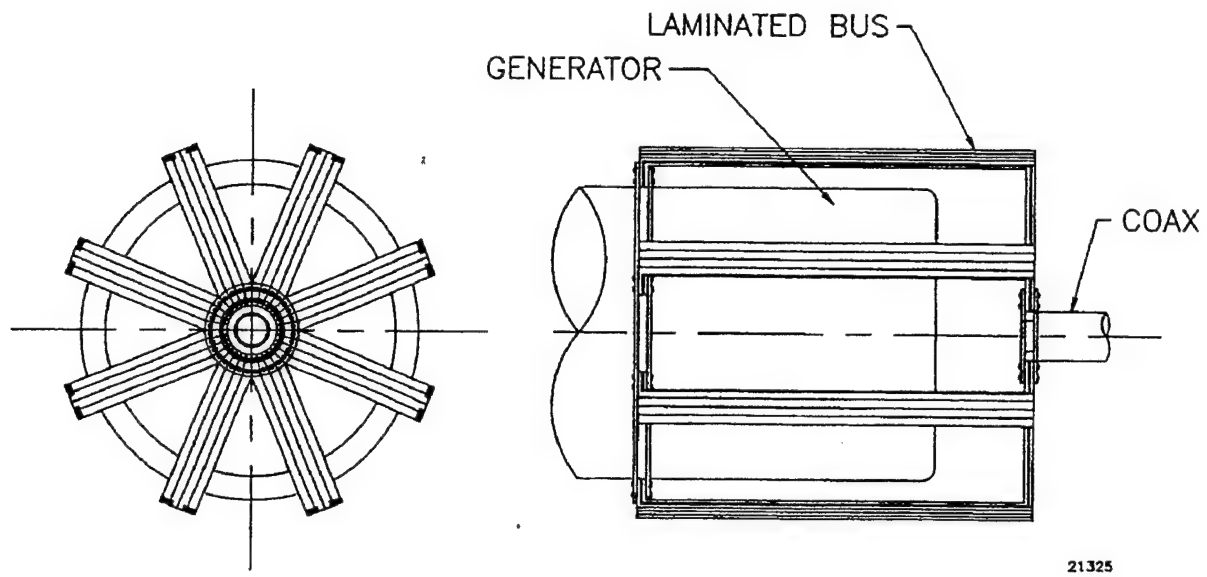


Figure 22. Generator/coax bus interface.

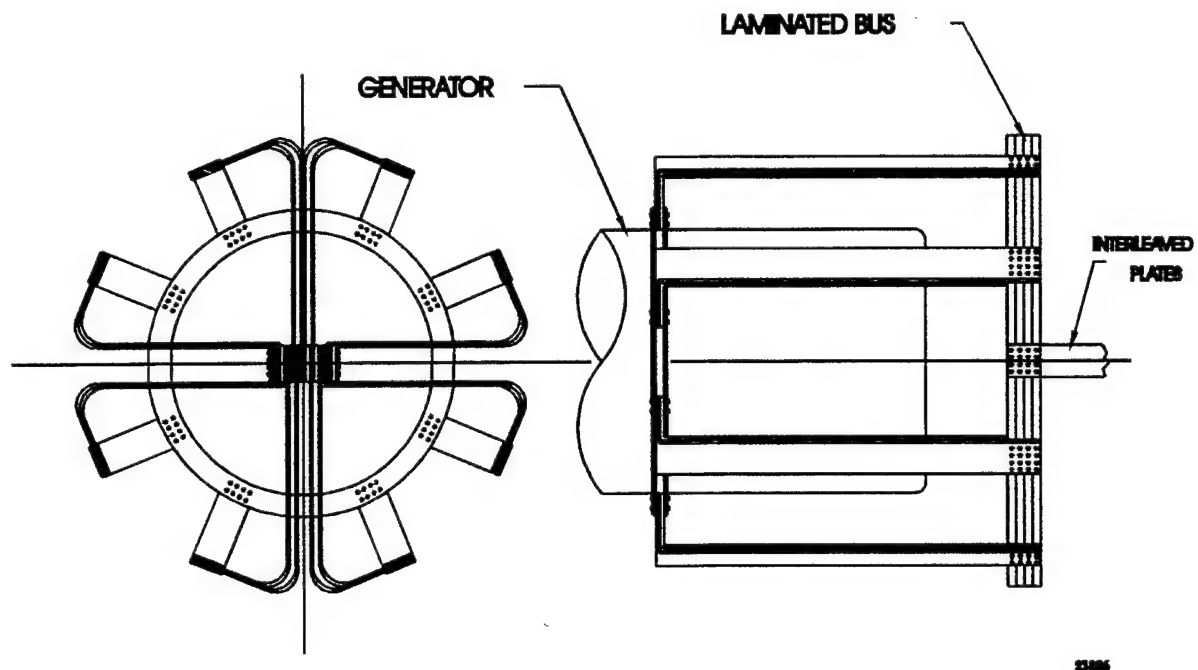


Figure 23. Generator/interleaved plate interface.

Laminated bus/transmission line interfaces for a coaxial and interleaved plate transmission line are shown in Figures 24 and 25, respectfully. As shown in Figure 24, the buses would extend radially from the coax and be bolted to an interface flange connecting to each polarity. With an interleaved plate transmission line, the flange is unnecessary. The laminated buswork are sandwiched between the parallel plates of the transmission line as shown in Figure 25.

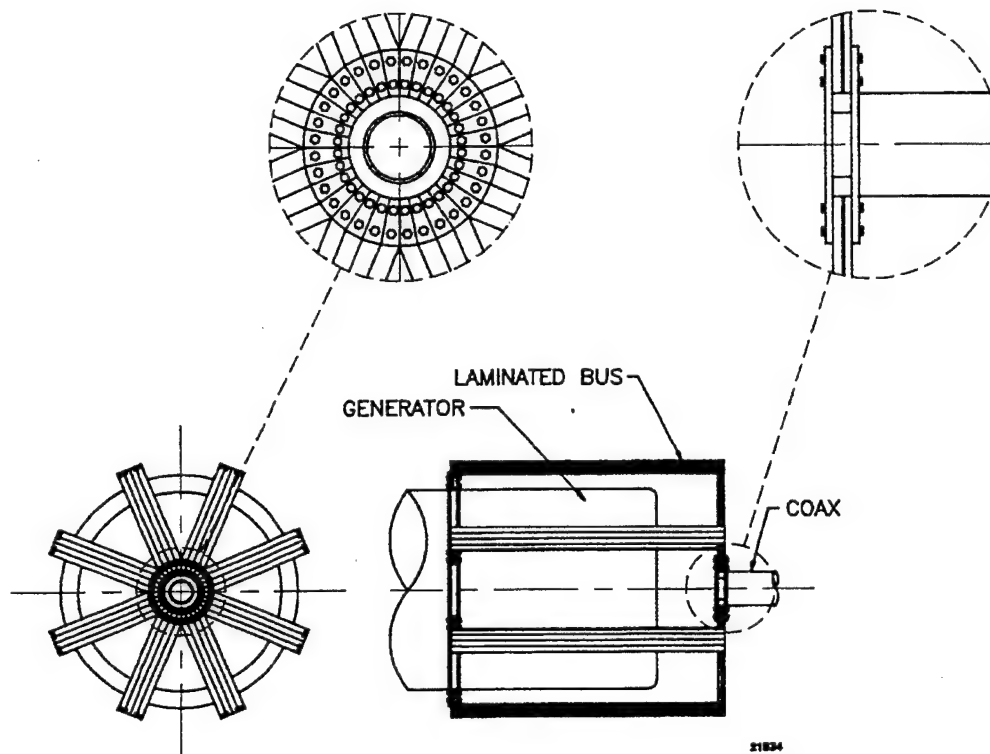


Figure 24. Laminated buswork of the flexible coupler would bolt to an interface flange on the coax transmission line.

Lamination of buswork allowing motion in all directions taken to the extreme is a cable. We examined cables. At the given current and required efficiency, approximately 500 400 MCM cables would be required. The large number of cables make termination very difficult and a very large volume would be required. We believe this prohibits their use in this application.

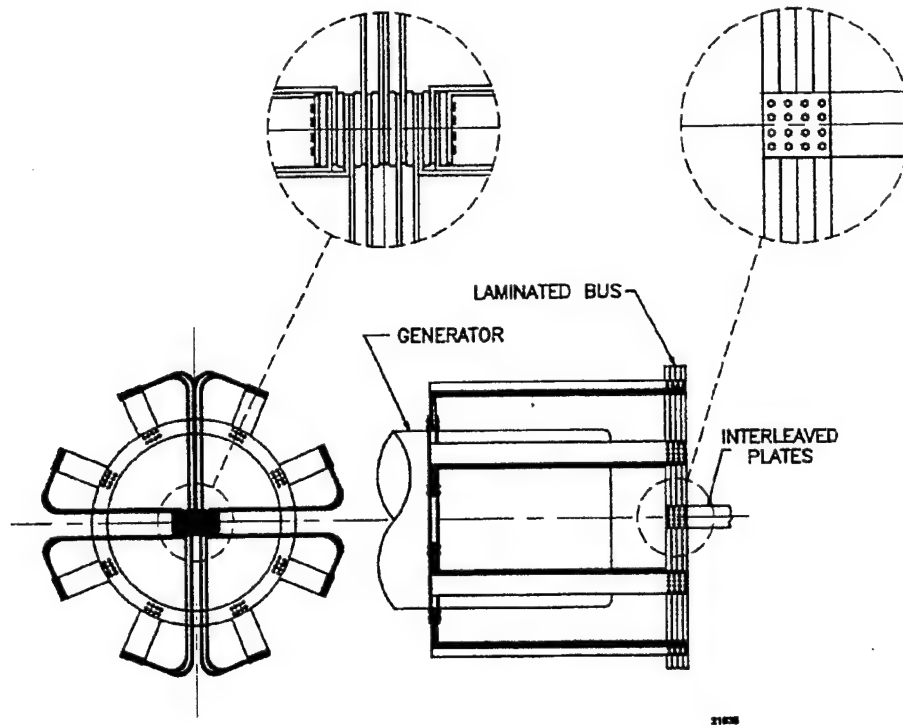


Figure 25. With an interleaved plate transmission line, the laminated buswork of the flexible coupler is sandwiched between the parallel plates.

4.4 Summary

In summary, there are two types of flexible couplers, those that promote sliding and those that promote flexure. Since all the design requirements are not available, rather than pursue a point design, we have developed the tools necessary to evaluate both sliding and flexure couplers. We believe both types can be designed to give any amount of isolation, once the requirement is known.

4.5 Conclusions

From our flexible coupler concept design, we can conclude the following:

1. Sliding interface requires separate fixtures for three degrees of freedom.
2. Sliding and flexural couplers can be designed to provide any required amount of isolation.
3. Our coupler will be the interface between the motor or generator and the transmission line. It is not an added fixture.
4. The large number of cables required make termination very difficult and prohibits their use in this application.

SECTION 5

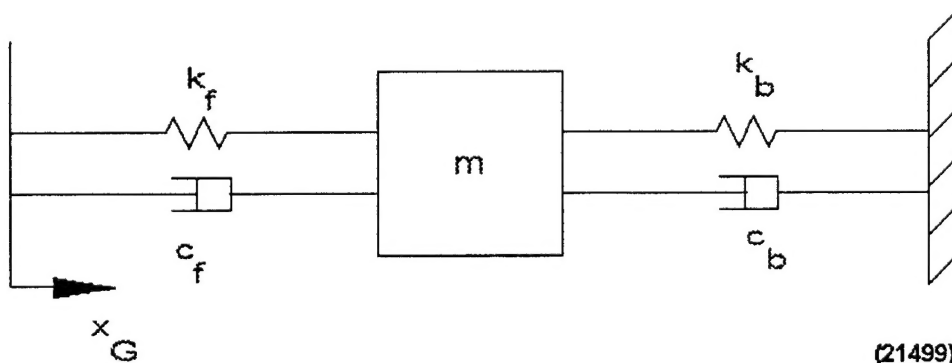
DYNAMIC ANALYSIS

5.1 Dynamic Model

To successfully design a flexible coupling, it is necessary to predict the dynamic behavior of the flexible coupling/transmission line/generator system. We modelled the system using lumped masses, springs, and dampers. For simplicity, the two degree of freedom system, shown in Figure 26, was used. More elaborate modelling may be required once the component designs have progressed further. The input function occurs at the generator attachment. This input was assumed to be sinusoidal to simplify the analysis and is given by:

$$x_G = x_0 \sin \omega t \quad (15)$$

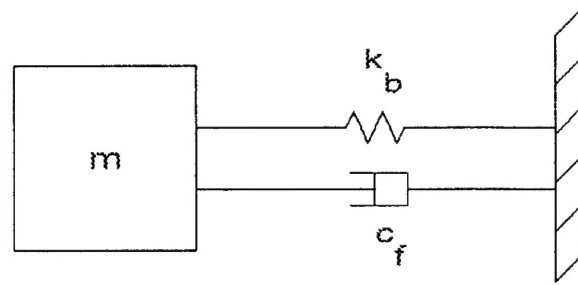
where: x_G = the generator displacement,
 x_0 = the amplitude of the oscillation,
 ω = the frequency of the oscillation, and
 t = time.



(21499)

Figure 26. We used a two degree of freedom system to gain a basic understanding of the dynamics involved.

The transmission line stiffness, k_b , will be significantly greater than the stiffness of the flexible coupler, k_f . Also, the damping of the transmission line will probably be low in comparison to the damping of the coupler. The model can then be reduced to the single degree of freedom system shown in Figure 27.



(21500)

Figure 27. Our single degree of freedom model.

Summing the forces gives the following equation:

$$m\ddot{x} + c_f\dot{x} + k_b x = k_f x_0 \sin \omega t \quad (16)$$

where m = the mass of the flexible coupling,
 \ddot{x} = the acceleration,
 c_f = the coupler damping constant, and
 \dot{x} = the velocity.

Solving for the transmitted force gives:

$$\frac{F_T}{k_f x_0} = \frac{\sqrt{1 + \left(2\zeta \frac{\omega}{\omega_n}\right)^2}}{\sqrt{\left(1 - \frac{\omega^2}{\omega_n^2}\right)^2 + \left(2\zeta \frac{\omega}{\omega_n}\right)^2}} \quad (17)$$

where: ω_n = the natural frequency of undamped oscillation, and
 ζ = the damping factor.

The above equation is typically called the transmissibility of the system, which is a measure of a system's isolation potential.

Transmissibility greatly depends on the damping factor. Damping, in general, is difficult to predict and is not commonly tabulated in references. It is often measured experimentally. As a result, we were unable

to determine the exact transmissibility of our candidate flexible coupler design. Instead, we calculated the transmissibility for a range of damping factors. As Figure 28 shows, the transmitted force approaches infinity with little damping near the frequency ratio of one. This is expected as the system is being resonated at its natural frequency. Large amplitudes and forces result. As the excitation frequency increases, the force transmission decreases.

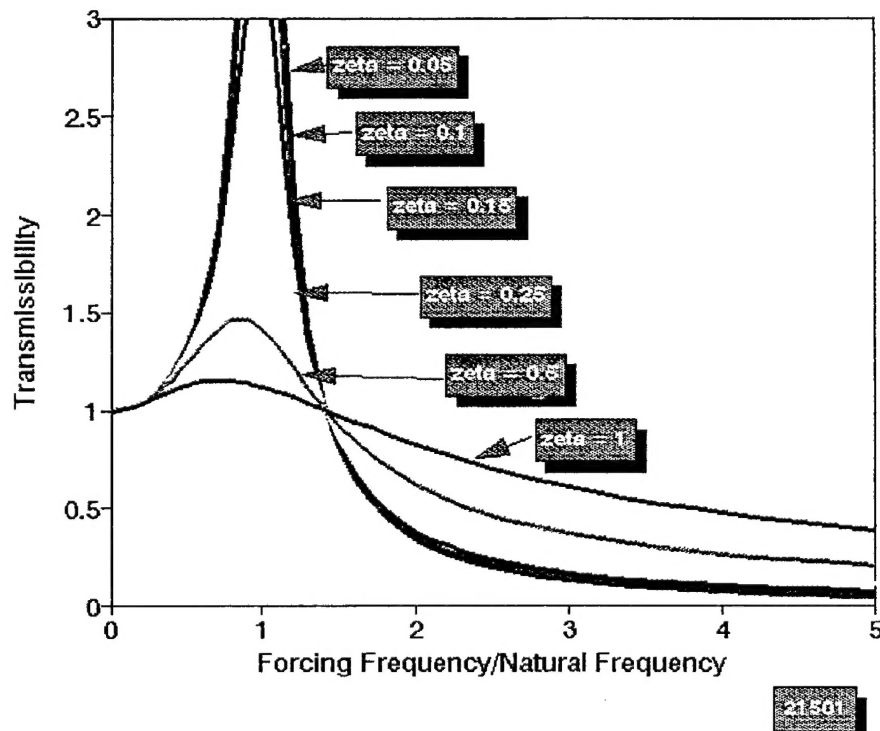


Figure 28. The transmitted force depends on the excitation frequency and damping factor.

5.2 Conclusions

Based on our analysis, we conclude:

1. A simplistic one degree of freedom model can be used to study the dynamic behavior of the flexible coupling. More elaborate modelling may be required once component designs have proceeded.
2. The transmissibility, a measure of the system's isolation potential, greatly depends on the damping in the flexible coupler.
3. Since experimental measurements are necessary to predict damping, it is impossible to determine the exact transmissibility of our candidate flexible coupler concepts.

SECTION 6

CONCLUSIONS AND RECOMMENDATIONS

Based on our Phase I work, we conclude:

1. A complete list of requirements and specifications is needed to select a coupler and to continue development.
2. More information is required to choose between coaxial or interleaved plates buswork. Currently, both configurations can be designed to meet Navy requirements. System level trade studies are required.
3. The interleaved plate transmission line concept is worthy of the Navy's additional consideration in choosing their buswork configuration.
4. Sliding or flexing type couplers are feasible. Both types should be examined once the requirements lists are complete.
5. The reduced number of connections favors laminated foils to cables. For 100 kA, over 500 400 MCM cables are required.
6. Flexing type coupler combines the transition from motor/generator to transmission line and isolation in one device.
7. Sliding interface requires separate fixtures for three degrees of freedom.
8. Sliding and flexural couplers can be designed to provide any required amount of isolation.
9. A simplistic one degree of freedom model can be used to study the dynamic behavior of the flexible coupling. More elaborate modelling may be required once component designs have progressed.
10. The transmissibility, a measure of the system's isolation potential, greatly depends on the damping in the flexible coupler.
11. Since experimental measurements are necessary to predict damping, it is impossible to determine the exact transmissibility of our candidate flexible coupler concepts.